LCA Case Studies

Including Oxidisation of Ammonia in the Eutrophication Impact Category

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Abstract. Oxygen depletion of lake and seawater is a serious condition with large implications for biodiversity. Therefore, in LCA, the potential oxygen demand of water emissions is estimated under the label eutrophication impact category. This impact category should contain the impact of water emissions on the total oxygen consumption in the receiving water. This means that it should include both primary and secondary oxygen consumption. In spite of this, the oxygen needed to oxidise ammonia has normally not been taken into account when quantifying the eutrophication impact category.

In this paper, weighting factors for ammonium/ammonia are suggested for the eutrophication impact category. It is shown that, for treated wastewater, the amount of oxygen needed for nitrification of ammonia is important when compared to the potential eutrophication calculated using the current recommended weighting factors. These weighting factors take into account oxygen needed to oxidise the organic matter in the wastewater emission and that needed to degrade the algae potentially grown due to the emission of nutrients.

Keywords: Ammonia; COD; denitrification; eutrophication impact category; Life Cycle Impact Assessment; nitrification; nitrogen; nutrification; oxidisation; oxygen consumption; phosphorus; urine separation; wastewater systems

Introduction

Eutrophication is an important impact category in Life Cycle Impact Assessment (LCIA). A state-of-the-art article by Finnveden and Potting (1999) shows that different impact assessment methods have been used, such as biomass production (Hauschild and Wenzel, 1998), oxygen consumption (Heijungs et al. 1992, Nord 1995) or non-aggregated indicators (Jensen et al. 1992). The non-aggregated indicators, proposed by Jensen et al. (1992), include emissions of nitrogen to air, emissions of nitrogen, phosphorus and BOD to water.

Oxygen depletion of lake and sea water is a serious condition with large implications for biodiversity, which is a strong argument for using total potential oxygen consumption representing the eutrophication impact category. Oxygen consumption can be characterised as primary or secondary. Primary oxygen consumption is the oxygen consumption caused by oxidation/degradation of substances, organic matter and ammonium contained in the emitted water, while secondary oxygen consumption is the oxygen consumption needed to degrade the algae potentially grown due to the emissions of nutrients.

In order to calculate the potential oxygen consumption, weighting factors are given in two manuals of LCA (Heijungs et al. 1992, Nord 1995). Both these manuals take into account secondary oxygen consumption (nutrification), caused by the oxygen consumption needed to degrade the algae potentially grown due to the emissions of nutrients, and primary oxygen consumption caused by the oxidation/degradation of emitted organic substances measured as COD. However, also emissions of ammonia to air and ammonium to water cause primary oxygen consumption due to the oxidation to nitrate in the receiving water. A compilation of potential contributions to oxygen consumption is presented in Table 1.

Table 1: Potential sources to oxygen consumption

Primary oxygen consumption	Secondary oxygen consumption
COD to water	Nitrogen to air
NH_3 to air (nitrification)	Nitrogen to water
NH_4^+ to water (nitrification)	Phosphorus to water

The estimation of primary oxygen consumption has the potential of being more accurate than that of the secondary one since the emission of organic matter and ammonia almost always leads to oxygen consumption. However, the current recommended weighting factors (Nord 1995, Table 2) imply a systematic under-estimation since the oxygen demand for nitrification is not accounted for. This oxygen consumption is not included in the COD (or BOD) values (APHA 1985) and no index is given for estimating it. When evaluating the effects of wastewater discharge, it is important to consider this oxygen demand since the major part of the nitrogen in untreated, and also in most treated, wastewater is ammonia (Henze et al. 1995).

When comparing different wastewater treatment methods, Ødegaard (1995) introduced the term 'Oxygen Compound Potential' (OCP), which includes both primary oxygen consumption (bacterial degradation of BOD and ammonia) and secondary oxygen consumption (bacterial degradation of algae caused by the nutrients, phosphorus and nitrogen). OCP, thus, closely resembles the measure required in LCA.

In this paper we suggest including weighting factors for the oxygen demand of nitrification in the eutrophication impact category. The importance of taking into account the oxidisation of ammonia is also illustrated by a case study of different wastewater systems.

1 Theory and its Application

1.1 Primary oxygen consumption – degradation of organic substances

To estimate the primary oxygen consumption, some assumptions are needed. Neither BOD nor COD will give an exact estimation of the amount of oxygen needed in the receiving water to degrade the emission of organic matter. BOD measures the oxygen demand for bacterial oxidation/degradation during the first five or seven days and thus underestimates the total, i.e. long-term, oxygen demand. However, in LCA, an estimation of the total potential oxygen depletion is needed (SETAC-Europe 1999). Therefore, the present recommendation is to use COD to estimate the primary oxygen consumption (Nord 1995, Table 2). The oxidisation of organic matter by micro-organisms to carbon dioxide is explained by the following expression (Henze et al. 1995):

$$C_{18}H_{19}O_9N + 17.5\ O_2 \rightarrow 18\ CO_2 + 8\ H_2O + NH_4^+$$

The primary oxygen consumption due to degradation of organic substances is considered in Heijungs et al. (1992) and Nord (1995).

1.2 Primary oxygen consumption – nitrification

Biological nitrification mainly involves two autotrophic bacteria genera, *Nitrosomonas* and *Nitrobacter,* where *Nitrosomonas* is responsible for the first step, the oxidation of ammonium to nitrite, and *Nitrobacter* for the second step, the oxidisation of nitrite to nitrate. From these processes both bacteria genera gain energy, which they use for building cell material (Tchobanoglous and Burton 1991). In the long run, this cell material is degraded and thus, the net reaction equations are written without taking the cell material into account (Henze et al. 1995).

$$NH_4^+ + 1.5\ O_2 \rightarrow NO_2^- + 2\ H^+ + H_2O \quad \textit{(Nitrosomonas)}$$

$$NO_2^- + 0.5\ O_2 \rightarrow NO_3^- \quad \textit{(Nitrobacter)}$$

$$NH_4^+ + 2\ O_2 \rightarrow NO_3^- + 2\ H^+ + H_2O \quad \textit{(Total reaction)}$$

From the total reaction, the oxygen demand for the nitrification of ammonium was calculated as 3.6 g O_2 per 1 g NH_4^+, or 4.6 g O_2 per 1 g NH_4^+-N. Naturally ammonia emitted to air and deposited in water also nitrifies. The oxygen demand for this is 4.6 g O_2 per 1 g NH_3-N, or 3.8 g O_2 per 1 g NH_3.

The primary oxygen consumption due to nitrification was not considered in Heijungs et al. (1992) or Nord (1995), and is therefore normally not considered in LCA-studies.

1.3 Secondary oxygen consumption

Many implicit assumptions are made in the present estimation of secondary oxygen consumption. The growth of algae depends on the availability of the substance that most severely limits their growth. In most inland waters, phosphorus is the substance which most severely limits the growth of algae, while in marine waters nitrogen or a combination of nitrogen and phosphorus limits the growth. Thus, depending on the type of recipient, Nord (1995) recommends different sets of weighting factors.

Important implicit assumptions in the present (Table 2) estimation of secondary oxygen consumption are:

1) that the oxygen set free by growing algae is totally lost before the algae are broken down,
2) that, apart from the phosphorus and/or nitrogen, no other substance or condition (e.g. temperature) limits the growth of algae and
3) that the growth limiting substance (N and/or P) is used by exactly one generation of algae, after which it is lost from the receiving water to sediment and/or atmosphere.

Due to these implicit assumptions, the estimation of the secondary oxygen consumption seems very uncertain compared to an estimation of the primary consumption.
The secondary oxygen consumption is considered in Heijungs et al. (1992) and Nord (1995). Hauschild and Wenzel (1998) consider the nutrient enrichment effect of the same sources.

1.4 Weighting factors

Table 2 shows the weighting factors for the eutrophication impact category given in Nord (1995), supplemented with the sug-

Table 2: Weighting factors for the impact category potential eutrophication from Nord (1995), with addition of weighting factors for ammonium and ammonia which are suggested in the present study

Substance ($g\ O_2/g$)	P-limited. Indices from Nord (1995)	N-limited + N to air. Indices from Nord (1995)	P-limited. Indices used in this study	N-limited + N to air. Indices used in this study
COD to water	1	1	1	1
NH_3 to air	0	16	3.8	19.8
NO_x to air	0	6	0	6
NO_3^- to water	0	4.4	0	4.4
NH_4^+ to water	0	15	3.6	18.6
P to water	140	0	140	0

gested factors for oxidisation of ammonium and ammonia. In LCA, normally no full fate analysis is done for the emitted substances, instead normally weighting factors based on a worst case scenario are used. Since the weighting factors are intended for calculating the worst case eutrophication potential, all ammonia emitted to air was assumed to be deposited in water.

2 Simulation of a Wastewater System

An environmental systems analysis of various systems for handling household wastewater and biodegradable household waste was performed to compare their overall performance. The computer-based modelling tool ORWARE (ORganic WAste REsearch) was used for the simulations. The ORWARE model is a collection of sub-models developed in several research projects, described in Sonesson (1998), Dalemo (1999) and Kärrman et al. (1999). ORWARE is based on the flows of 43 substances, including plant nutrients such as phosphorus and nitrogen, and heavy metals such as cadmium. From the inflow of waste/wastewater, described by its content of these 43 substances, the ORWARE model simulates the emissions to air and water, the generation of solid waste and the use of energy and other resources.

The present study dealt only with the running of the systems, and aspects of their construction were not included. The different waste and wastewater systems were simulated for a settlement with 20 000 inhabitants and the transport distance to field was 10 km.

Processes included in the study were:
- production and distribution of drinking water
- collection and transport of wastewater and of solid organic waste to treatment
- treatment of wastewater and solid organic waste
- discharges of treated wastewater to receiving waters
- transport of treatment products to, and their utilisation on, arable land
- transport of waste from wastewater pre-treatment to, and degradation on, a landfill

The study is described in full detail in Kärrman et al. (1999). In this paper, only the results for the eutrophication impact category are presented for two of the systems studied;

1) a well performing conventional wastewater system and
2) an alternative sewage system where a conventional sewage treatment plant (for faeces and grey-water) is supplemented with source separation, collection and reuse of urine.

In this paper, three versions of the conventional system are also presented (alternative A, B and C).

The flow of nitrogen differs among the alternatives. Alternative A is not designed for nitrogen removal and less than 10% of nitrogen is removed in the treatment plant. In alternative B, the biological process is supplemented with nitrification through aeration. Alternative B has the same low degree of nitrogen removal as alternative A, but 90% of the ammonia is nitrified before discharge. In alternative C, nitrification and denitrification are included in the wastewater treatment plant, which altogether removes 70% of the nitrogen from the wastewater. In the urine separation system, alternative D, no special nitrogen removal processes are included in the wastewater treatment plant. However, the nitrogen-rich urine is source-separated, collected and used as a fertiliser on arable land. The source separation of urine is assumed to reduce 80% of the flows of nitrogen in the wastewater system, and the total reduction of nitrogen from the wastewater is also approximately 80% in this system. An overview of the four systems is given in **Table 3**.

3 Results and Discussion

The calculated nitrogen-limited eutrophication due to the emitted treated wastewater from the four alternatives is presented in **Fig. 1**. In alternative A, the effect on potential oxygen consumption of taking oxygen demand for nitrification into account is far more important than the oxygen demand due to organic matter (COD). For the other alternatives, the primary oxygen demand due to organic matter is roughly of the same order as that for the primary oxygen demand due to ammonium. The difference in oxygen consumption is 15% between alternative A, where a large amount of ammonia is discharged, and alternative B, where 90% of the ammonia is nitrified. However, for all alternatives, the secondary effects of the discharge of nitrogen have a much larger influence than the oxygen needed for nitrification. Thus, one effi-

Table 3: Management of wastewater in the four systems

	A) Conventional system	B) Conv. syst. with nitrification	C) Conv. syst. with nitrogen removal	D) Urine separation system
Fractions collected	1) Wastewater	1) Wastewater	1) Wastewater	1) Urine 2) Faeces and bath, dish and laundry water
Collection system	1) Sewer	1) Sewer	1) Sewer	1) Urine pipe 2) Sewer
Treatment	1) Mech., biol. (no N-removal) and chem. treatment	1) Mech., biol. (incl. nitrification) and chem. treatment	1) Mech., biol. (incl. nitrogen removal) and chem. treatment	1) Storage tank 2) Mech., biol. & chem. treatment (faeces + bath, dish and laundry water)
Residuals	1) Water to recipient 2) Sludge to arable land 3) Pre-treatment sludge to landfill	1) Water to recipient 2) Sludge to arable land 3) Pre-treatment sludge to landfill	1) Water to recipient 2) Sludge to arable land 3) Pre-treatment sludge to landfill	1) Water to recipient 2) Urine and sludge to arable land 3) Pre-treatment sludge to landfill

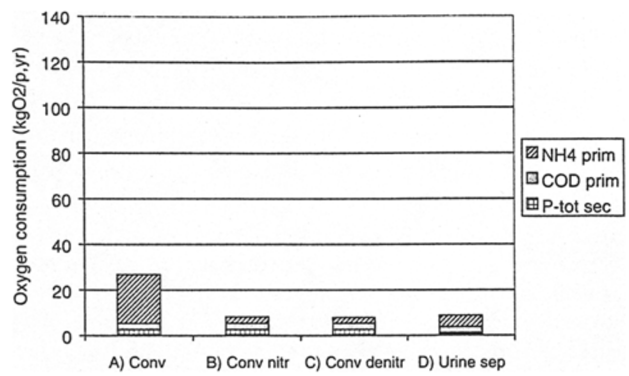

Fig. 1: Simulation results using weighting factors for nitrogen-limited eutrophication including nitrogen to air from Table 2. Primary oxygen consumption components are marked 'prim' and secondary oxygen consumption components are marked 'sec'

cient way of decreasing eutrophication is nitrogen removal. In alternative C, this is done by biological nitrification and denitrification, whileit is done by urine separation in alternative D. The difference in oxygen consumption between alternative A (no special nitrogen removal) and alternative C (nitrification/denitrification) is 65%.

In alternative D, the wastewater treatment plant contains no special nitrification step, which means that the main fraction of the nitrogen emitted with the wastewater is in the form of ammonium. This is, however, of minor importance since the oxygen demand is 70% lower in alternative D compared to alternative A (Fig. 2).

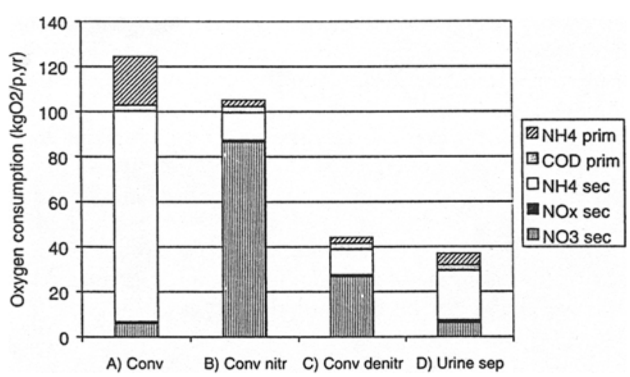

Fig. 2: Simulation results using weighting factors for phosphorus-limited eutrophication including NH_3 to air, from Table 2. Primary oxygen consumption components are marked 'prim' and secondary oxygen consumption components are marked 'sec'

The oxygen consumption is much lower per person and year under phosphorus-limited conditions compared to nitrogen-limited conditions (Fig. 1 and 2). The reason for this is a high phosphorus removal, more than 95%, in all alternatives, while the nitrogen removal for all scenarios is in the range of 10-80%. Consequently, the relative contribution to oxygen consumption from nitrification is larger under phosphorus-limited conditions compared to under nitrogen-limited conditions.

For phosphorus-limited conditions, it is interesting to note that a denitrification process is superfluous. Alternative B, only containing nitrification, contributes no more to oxygen consumption than alternative C, which includes nitrification and denitrification. It is also interesting to note that the order of ranking changes when comparing Fig. 1 and 2. In Fig. 2, the urine separation system, alternative D, contributes slightly more to oxygen consumption than alternatives B and C. The only reason for this is the primary effect of the ammonium discharge and its oxygen consumption due to nitrification. The wastewater treatment plant alternatives B and C include a biological nitrification process (through mechanical aeration), while no such process is assumed to be included in the urine separation system.

These results show that the oxidisation of ammonia has a significant effect on phosphorus-limited eutrophication for conventional wastewater treatment plants. In recipients with P-limited eutrophication, a nitrification process in the wastewater treatment is obviously important to minimise the oxygen consumption. An even more important measure, however, is to remove phosphorus to a high degree. In all studied alternatives, at least 95% of the phosphorus in wastewater is removed through chemical precipitation.

For nitrogen-limited eutrophication, the influence of secondary oxygen consumption from nitrogen discharge overshadows other contributions. For a conventional wastewater treatment plant, the oxygen demand due to nitrification of ammonia is more important than that due to organic matter. In waters where maximal eutrophication potentially appears, it is important to apply a treatment process that removes both phosphorus and nitrogen, and which nitrifies the remaining nitrogen. This could either be achieved by biological processes or by source separation of urine.

4 Conclusions

The oxygen consumption in receiving waters from oxidisation of ammonia needs to be included in the eutrophication impact category, since this contribution is significant. It is especially important under phosphorus-limited conditions since the oxygen consumption due to oxidisation of ammonia often is the single largest contributor to the total oxygen consumption of effluent wastewater from a plant with chemical precipitation or other high-degree removal of phosphorus and organic matter. Under these conditions, inclusion of nitrification in the sewage system efficiently decreases the oxygen demand of the emitted water.

Under nitrogen-limited conditions, the oxygen consumption due to nitrification is, for wastewater treated in a well functioning conventional sewage treatment plant, usually larger than that due to organic matter. They are approximately of the same size if nitrification or nitrogen removal has been included in the sewage system.

Urine separation systems significantly decrease the amount of nitrogen emitted from the wastewater treatment plant. Under phosphorus-limited conditions, including nitrification in the wastewater treatment plant can further decrease the potential oxygen consumption.

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Announcement of an LCA Case Study

Life Cycle Assessment for Lithium and Lithium Compounds

Lithium, a light metal, is getting increasingly important in different sectors of the economy. It can, for example, be used for batteries or in metal alloys. The environmental consultancy ESU-services has investigated the environmental impacts of lithium production in a life cycle assessment (LCA) study. The first part of this study gives general information for lithium production. The resources, production and uses are described. The chapter also provides an overview of the major companies in the market. The environmental impacts of lithium production are investigated in the second part from cradle to gate in a life cycle assessment (LCA). The inventory is split up into four main stages according to the intermediate products of lithium processing: concentration of lithium brine in South America, production of lithium carbonate, lithium chloride and metallic lithium. Additionally, water pumps and the production of potassium chloride are investigated for the inventory. Internal data for the environmental impacts of production processes of the two major producers of lithium were not available. Thus, the study mainly uses published information. About 700MJ-eq of non-renewable energy resources are used to produce one kilogram of lithium. Major energy uses in the life cycle arise from the electrolysis of lithium metal and from the use of soda and hydrogen chloride in processing. The environmental impacts for the pre-products lithium carbonate and lithium chloride are much lower than for the metallic lithium. The mining of lithium in South American deserts could also have important local effects on the groundwater level that cannot be accounted for with the LCA method and its 'global view'. The results of the inventory are meant to be used in LCA studies of technical products, such as batteries, where lithium or lithium compounds are one of the necessary materials.

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